

# Valence and sea quarks in the nucleon

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**Abstract.** In this contribution, we discuss the spin and flavor content of the proton in the framework of the unquenched quark model, and address the role of valence and sea quarks in the nucleon.

## 1. Introduction

The role of valence and sea quarks in the nucleon is addressed in the framework of the unquenched quark model. The constituent quark model (CQM) describes the nucleon as a system of three constituent, or valence, quarks. Despite the successes of the CQM (*e.g.* masses, electromagnetic couplings, magnetic moments), there is compelling evidence for the presence of sea quarks from the measurement of the flavor asymmetry of the proton and the so-called proton spin crisis. The role of the pion cloud in the nucleon has been the subject of many studies [1, 2, 3], and was shown to hold the key to understand the flavor asymmetry and the spin-crisis of the proton. Recently, it was pointed out these two properties are closely related: angular momentum conservation of the pionic fluctuations of the nucleon leads to a relation between the flavor asymmetry and the contribution of orbital angular momentum to the spin of the proton  $\mathcal{A}(p) = \Delta L$  [4]. This identity can be understood from the fact that the flavor asymmetry is a matrix element in isospin space, and the orbital angular momentum in spin space with the same values of the quantum numbers.

The aim of this contribution is to study the properties of the nucleon in the unquenched quark model (UQM) at the level of a toy model in which only the effects of the pion cloud is taken into account. It is shown that the pion cloud offers a qualitative understanding of the results obtained in previous numerical studies [5], and thus provides important insights into the properties of the nucleon.

**Table 1.** Spin and flavor content of the proton in the constituent quark model (CQM) and the unquenched quark model (UQM).

	CQM	UQM
$\mathcal{A}(p) = \Delta L$	0	$\frac{2a^2 - b^2}{3(1 + a^2 + b^2)}$
$\Delta u$	$\frac{4}{3}$	$\frac{4}{3} - \frac{38a^2 + b^2 - 16ab\sqrt{2}}{27(1 + a^2 + b^2)}$
$\Delta d$	$-\frac{1}{3}$	$-\frac{1}{3} + \frac{2a^2 + 19b^2 - 16ab\sqrt{2}}{27(1 + a^2 + b^2)}$
$\Delta s$	0	0
$\Delta\Sigma = \Delta u + \Delta d + \Delta s$	1	$1 - \frac{4a^2 - 2b^2}{3(1 + a^2 + b^2)}$
$g_A = \Delta u - \Delta d$	$\frac{5}{3}$	$\frac{5}{3} - \frac{40a^2 + 20b^2 - 32ab\sqrt{2}}{27(1 + a^2 + b^2)}$

## 2. Flavor and spin content

In the unquenched quark model the effect of the quark-antiquark pairs is taken into account via a  $^3P_0$  creation mechanism. The resulting baryon wave function is given by [5]

$$|\psi_A\rangle = \mathcal{N} \left[ |A\rangle + \sum_{BCIJ} \int d\vec{K} k^2 dk |BC, l, J; \vec{K}, k\rangle \frac{\langle BC, l, J; \vec{K}, k | T^\dagger | A \rangle}{\Delta E_{BC}(k)} \right], \quad (1)$$

where  $\Delta E_{BC}(k) = M_A - E_B(k) - E_C(k)$  is the energy difference calculated in the rest frame of the initial baryon  $A$  with  $E_B(k) = \sqrt{M_B^2 + k^2}$  and  $E_C(k) = \sqrt{M_C^2 + k^2}$ . The operator  $T^\dagger$  is the  $^3P_0$  quark-antiquark pair creation operator [5, 6];  $\vec{k}$  and  $l$  denote the relative radial momentum and orbital angular momentum of  $B$  and  $C$ , and  $J$  is the total angular momentum  $\vec{J} = \vec{J}_B + \vec{J}_C + \vec{l}$ . The strength of the  $^3P_0$  coupling is determined from the flavor asymmetry of the proton.

In this contribution, we employ a simplified version of the UQM in which only the contribution of the pion cloud is taken into account. Table 1 shows the results for the flavor and spin content of the proton. In the UQM, the three coefficients  $a^2$ ,  $b^2$  and  $ab$  are expressed in terms of an integral over the relative momentum  $k$  which depends on the  $^3P_0$  coupling strength. We note, that the results for the UQM in Table 1 also hold for the meson-cloud model in which the coefficients  $a$  and  $b$  multiply the  $N\pi$  and  $\Delta\pi$  components of the nucleon wave function. The  $ab$  term denotes the contribution from the cross terms between the  $N\pi$  and  $\Delta\pi$  components. In the UQM the value of the cross term  $ab$  is not equal to the product of  $a$  and  $b$ , although it turns out that the numerical values are close.

Since the UQM contains the full spin and isospin structure, it satisfies the relation between the flavor asymmetry and the contribution of the orbital angular momentum to the spin of the proton  $\mathcal{A}(p) = \Delta L$  [4], and therefore  $\Delta\Sigma = 1 - 2\Delta L$ . This relation does not hold for the chiral quark model of [7, 8] in which the orbital angular momentum is enhanced with respect to the flavor asymmetry  $\Delta L = 3\mathcal{A}(p)/2$  as a consequence of the requirement of a helicity flip of the quark.

Table 2 shows the results for the spin and flavor content of the proton normalized to the proton flavor asymmetry. The third column is normalized to the E866/NuSea value [9], and the fourth column to the somewhat higher NMC value [10]. The experimental values of the spin content were obtained by the HERMES [11] and the COMPASS [13] Collaborations. In Table 2, we show the HERMES results.

**Table 2.** Spin and flavor content of the proton normalized to the flavor asymmetry, UQM1 using the E866/NuSea value [9] and UQM2 using the NMC value [10].

	CQM	UQM1	UQM2	Exp	Ref
$\mathcal{A}(p)$	0	*0.118	*0.158	$0.118 \pm 0.012$ $0.158 \pm 0.010$	[9] [10]
$\Delta u$	4/3	1.132	1.064	$0.842 \pm 0.013$	[11]
$\Delta d$	-1/3	-0.368	-0.380	$-0.427 \pm 0.013$	[11]
$\Delta s$	0	0	0	$-0.085 \pm 0.018$	[11]
$\Delta \Sigma$	1	0.764	0.684	$0.330 \pm 0.039$	[11]
$g_A$	5/3	1.500	1.444	$1.2701 \pm 0.0025$	[12]

The probability that a proton fluctuates in  $n\pi^+$

$$|\langle n\pi^+ | p \rangle|^2 = \frac{2a^2}{3(1 + a^2 + b^2)} = 0.180 , \quad (2)$$

(UQM1 value) is in close agreement with the experimental value  $0.17 \pm 0.01$  determined in an analysis of forward neutron production in electron-proton collisions at 300 GeV by the H1 and ZEUS Collaborations at DESY [14, 15]. The UQM2 value is somewhat higher 0.241. The total probability for a pion fluctuation of the proton is given by

$$|\langle N\pi | p \rangle|^2 + |\langle \Delta\pi | p \rangle|^2 = \frac{a^2 + b^2}{1 + a^2 + b^2} = 0.455 , \quad (3)$$

(UQM1 value), in good agreement with the value of 0.470 as determined in an analysis of the quark distribution functions measured in Drell-Yan experiments and semi-inclusive DIS experiments [16]. Also in this case, the UQM2 value, 0.609, is about 30 % higher than the UQM1 value.

### 3. Summary and conclusions

In this contribution, we studied the properties of the proton in the framework of the unquenched quark model in which the  $^3P_0$  coupling strength was normalized to the observed value of the proton flavor asymmetry. It was shown that the pion fluctuations help to understand the discrepancies between the constituent quark model and the experimental data. Their inclusion leads to a reduction of quark model value of  $\Delta u$  and  $g_A$ , and give rise to a sizeable contribution (25 - 30 %) of orbital angular momentum to the spin of the proton. In addition, it was found that the probabilities for pion fluctuations in the UQM are in good agreement with the values determined in analyses of the available experimental data.

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